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Developmental Relations Among Motor and Cognitive Processes and Mathematics Skills

Helyn Kim, and Chelsea A. K. Duran
University of Virginia

Claire E. Cameron
University at Buffalo, State University of New York

David Grissmer
University of Virginia

This study explored transactional associations among visuomotor integration, attention, fine motor coordination, and mathematics skills in a diverse sample of one hundred thirty-five 5-year-olds (kindergarteners) and one hundred nineteen 6-year-olds (first graders) in the United States who were followed over the course of 2 school years. Associations were dynamic, with more reciprocal transactions occurring in kindergarten than in the later grades. Specifically, visuomotor integration and mathematics exhibited ongoing reciprocity in kindergarten and first grade, attention contributed to mathematics in kindergarten and first grade, mathematics contributed to attention across the kindergarten year only, and fine motor coordination contributed to mathematics indirectly, through visuomotor integration, across kindergarten and first grade. Implications of examining the hierarchical interrelations among processes underlying the development of children's mathematics skills are discussed.

Mathematics learning during early elementary school provides the foundation for students' later academic achievement (Duncan et al., 2007) and, in the long-term, for success in an increasingly competitive job market that values quantitative abilities (National Mathematics Advisory Panel, 2008). In recent years, visuomotor integration, attention, and fine motor coordination have been linked to children's early and long-term mathematics achievement (e.g., Cameron et al., 2012; Carlson, Rowe, & Curby, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Sortor & Kulp, 2003). These processes have been featured centrally in studies assessing the possible role of motor skills in mathematics learning. Yet, beyond well-established associations among these processes, there is little clarity regarding when and to what degree they contribute to each other and to mathematics skills in early elementary school. Such contributions are difficult to discern because of their rapid and intertwined development during this period (Korkman, Kirk, & Kemp, 1998).

In addition, few studies have included multiple processes simultaneously across multiple time points to identify their dynamic, transient, and indirect effects. Thus, the unique and combined contributions that each process may make toward the development of mathematics skills remain largely unknown. This study examines the dynamic, longitudinal, and reciprocal contributions of visuomotor integration, attention, and fine motor coordination to mathematics skills in a diverse sample of early elementary students, using an autoregressive, cross-lag (ACL) approach. This study follows two cohorts of children over 2 years: in one cohort, from kindergarten through first grade and, in the other cohort, from first through second grade.

Theoretical Perspectives on Interrelations Between Motor and Cognitive Development

Decades of psychological theory and research have established that motor and cognitive development

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Correspondence concerning this article should be addressed to Helyn Kim, Brookings Institution, Center for Universal Education, 1775 Massachusetts Ave. NW, Washington, DC 20036. Electronic mail may be sent to hk3a@virginia.edu.

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are inextricably intertwined in infancy and early childhood (e.g., Adolph, 2008; Davis, Pitchford, & Limback, 2011; Diamond, 2007; Piaget, 1952). When approached from a dynamic systems perspective, individual processes are expected to exhibit both stability and change over time; furthermore, the changes in each skill are expected to reciprocally affect the trajectory of other skills, as the entire system seeks to coordinate among all skills (e.g., Thelen, 2005). Consistent with dynamic systems theory, recent advances in neuroscience and the science of human movement have uncovered compelling links between motor and cognitive development. For instance, the development of fine motor skills requires functional networks that substantially overlap with the neural structures underlying certain higher order, abstract cognitive processes, including attentional control (Floyer-Lea & Matthews, 2004). Several theoretical accounts have been offered to explain how motor and cognitive development, in particular, are related. We explore two such accounts: reciprocity and automaticity. However, the scarcity of longitudinal work in this area makes it difficult to ascertain which of the theories may be plausible. Furthermore, a single theoretical account may not on its own fully explain the associations. Thus, these accounts are useful for shaping our expectations regarding potential changes in relations among constructs over time but are not presented as competing alternatives.

Reciprocity

The notion of reciprocity suggests that motor skills and cognition codevelop following experiences that support both as children interact with their environment (Campos et al., 2000). For instance, in infancy, learning to control, coordinate, and integrate multiple body movements into a coherent organized system supports cognitive capacities, which in turn allows for the acquisition of more varied and complex motor skills (Adolph, 2008). As children acquire new behavioral and cognitive abilities, brain regions interact with each other, generating extensive patterns of connectivity early in development (Johnson, 2001). Furthermore, as children develop, motor and cognitive skills appear to differentiate as their neural substrates become highly structured and functionally specialized (Johnson, 2001); therefore, reciprocity between skills may be transient over time.

Automaticity

The notion of automaticity suggests that mastery in one foundational skill supports more complex task performance and development of other skills. From this perspective, codevelopment of motor skills and cognition reflects dependence of complex skills, such as mathematics, upon more rudimentary skills, such as motor competence. This theory assumes that when children are asked to simultaneously perform multiple tasks that have both motor and cognitive components (Cameron et al., 2012), both processes will compete for limited attentional resources. In a school setting, automaticity in a motor-based classroom task may free up attentional resources for learning complex concepts (Cameron et al., 2015). Conversely, children lacking such automaticity may have to attend more carefully to the motor aspects of the task, placing a constraint on their learning.

It is possible that, depending on the skills in question or time in development, either reciprocity or automaticity applies. As children transition to formal school and move into more structured environments (La Paro, Rimm-Kaufman, & Pianta, 2006), they need to control their own bodies to accomplish behavioral and learning goals (Kim et al., 2015). Using their motor skills to interact with the environment is a key means by which children come to understand the world and develop academically (e.g., Adolph, 2008). Therefore, the early elementary school years are an ideal time to investigate dynamic associations among specific skills.

Visuomotor Integration, Attention, Fine Motor Coordination, and Mathematics

In early childhood, children make great developmental strides in visuomotor integration, attention, and fine motor coordination. This concurrent development suggests either codeveloping, or perhaps even codependent, processes (Fuhs, Nesbitt, Farran, & Dong, 2014). These three processes are also a focus here because they are strong predictors of concurrent and long-term mathematics achievement, even after controlling for other predictors like demographic information and previous academic performance (e.g., Cameron et al., 2012; Carlson et al., 2013; Grissmer et al., 2010; Luo, Jose, Huntsinger, & Pigott, 2007).

Visuomotor Integration

Visuomotor integration is a complex and multifaceted construct that relies on both attention and fine motor coordination, as well as their integration, and as such is critical to adjustment to multiple aspects of school performance including

mathematics (e.g., Carlson et al., 2013). Visuomotor integration skills are typically tested using design copying tasks, in which children are presented an object or image and attempt to replicate it using pencil and paper (Korkman et al., 1998). Design copying performance requires visual–spatial processing, including the ability to see the object or image as a set of parts, flexibility in shifting attention back and forth between the parts of the object or image and the entire object or image as a whole, creating a mental representation of the object or image, and sequencing finger movements in recreating the object (Carlson et al., 2013).

Developmental course. As the name suggests, visuomotor integration depends on visual and motor skills being in place before they can be integrated (Decker, Englund, Carboni, & Brooks, 2011; Korkman et al., 1998). Age explains a large portion of visuomotor integration, which develops rapidly between ages 4 and 7, and more slowly through at least age 12 (Decker et al., 2011). Children use visuomotor integration when working with manipulatives, writing, or drawing—activities that are prevalent in early elementary grades. Importantly, the "integration" component of visuomotor integration may arise from attentional processes (Decker et al., 2011).

Relevance for mathematics. Visuomotor integration is robustly linked to children's concurrent and longitudinal mathematics achievement (e.g., Cameron et al., 2012; Carlson et al., 2013). In a cross-sectional sample of 5- to 18-year-olds, Carlson et al. (2013) found that visuomotor integration was associated with mathematics achievement, even after controlling for gender, socioeconomic status, fine motor coordination, and IQ. The strong association between visuomotor integration and mathematics may arise because the components that are necessary for successful visuomotor integration are also implicated in mathematics learning (Kim & Cameron, 2016, Decker et al., 2011; Gunderson, Ramirez, Beilock, & Levine, 2012). For example, children need to discriminate between symbols (e.g., numbers and arithmetic signs) and copy math problems correctly, which involve some aspect of visuomotor integration (i.e., visual, motor, spatial, and attentional processes). Understanding mathematics concepts also requires children to interact with physical objects (Ginsburg, 1977), form mental representations of objects and cognitively manipulate them (Hegarty & Kozhevnikov, 1999), spatially represent and interpret numerical information (Gunderson et al., 2012), and use adaptive strategies to solve problems (Geary & Burlingham-Dubree, 1989). Thus, having better visuomotor integration may support development of certain mathematics skills.

In addition, neurobiological research indicates that the parietal cortex is an area of the brain that is particularly active during both visuomotor integration tasks and numerical processing (Dehaene, 1992). Relatedly, visuomotor integration may contribute to the development of the mental number line (Gunderson et al., 2012) as well as in developing the understanding of part–whole relationships (Verdine et al., 2014), both of which are important for mathematics performance. When children are first learning how to count, they typically rely on their motor skills to physically touch each object. But, once this process becomes automated, they no longer have to touch the objects and, instead, are able to rely on mental–spatial representations of the objects being counted (Assel, Landry, Swank, Smith, & Steelman, 2003).

Attention

Attention is a multidimensional construct considered part of executive functioning (EF)—a set of cognitive processes that help children coordinate their goal-directed responses to novel or complex situations (Garon, Bryson, & Smith, 2008). Attention comprises several subfunctions, such as selective focusing and sustaining of attention, regulation of arousal, and shifting or dividing attention (Ruff & Rothbart, 2001). Attentional processes are required to focus children's cognitive resources to execute goals, including complex learning tasks in the classroom (Zelazo, Muller, Frye, & Marcovitch, 2003). In the current study, attention refers to selective and sustained attention toward visual stimuli (Korkman et al., 1998).

Developmental course. The development of attention is a multistage process, in which different subfunctions develop at different times (Ruff & Rothbart, 2001). In general, the development of attention follows a roughly logarithmic trajectory, with rapid development between ages 4 and 7, and continued improvement through early adulthood (Beery & Beery, 2004). Longitudinal studies suggest that selective and sustained attention, as measured by the visual search task used herein, reach maturity as early as 6 years of age (Klenberg, Korkman, & Lahti-Nuuttila, 2001). Classroom activities constantly require children to use their attention, for instance, when shifting focus from one task to another and also when sustaining attention for the length of a lesson to process and store information in the presence of distractions (Ruff & Rothbart, 2001).

Relevance for mathematics. Children's attentional abilities underlie development of mathematics skills (Geary, 2013), even after accounting for general intelligence (e.g., Blair & Razza, 2007). Mathematics tasks in early childhood typically require children to focus and shift their attention between distinct but closely related dimensions of objects, such as color and shape or between specific aspects of math problems (Blair, Knipe, & Gamson, 2008; Bull & Lee, 2014; Clements, Sarama, & Germeroth, 2016). The ability to control attention to hold information in mind while simultaneously engaging in other processes may be useful for coding mathematical rules, as well as interpreting and comparing information across multiple modalities, which facilitates efficient performance on math tasks (Kolkman, Kroesbergen, & Leseman, 2014; Zelazo et al., 2003). Moreover, explicit understanding of new mathematical concepts depends on attentional resources carried out in the prefrontal cortex of the brain, which must develop in order to accommodate higher levels of abstraction (Geary, 2013; Rivera, Reiss, Eckert, & Menon, 2005).

As children mature and task performance becomes automated, activation in the prefrontal regions decreases (Rivera et al., 2005). In one study, attention contributed to 7- to 10-year-old children's mathematics above and beyond intelligence, fine motor coordination, and even visuomotor integration, whereas the latter two did not contribute to mathematics after accounting for attention (Sortor & Kulp, 2003). But development in mathematics skills may also increase general executive processing (Welsh, Nix, Blair, Bierman, & Nelson, 2010). For instance, Fuhs et al. (2014) found longitudinal bidirectional associations between EF and mathematics achievement in a sample of 4-year-olds. However, although EF continued to be a strong predictor of children's later mathematics gains at age 5, mathematics achievement was no longer a predictor of gains in EF (Fuhs et al., 2014). One reason for possible bidirectional associations between attentional processes and mathematics earlier in development may be because mathematics activities provide children with opportunities to exercise attentional processes, such as when shifting attention across elements of a problem while maintaining relevant mathematical rules in mind (Clements et al., 2016).

Fine Motor Coordination

Fine motor coordination encompasses muscle movements, including coordination and dexterity in the fingers, motor sequencing, and fine motor speed and accuracy (Cameron et al., 2015). Hence, though considered a motor rather than higher order cognitive process here, fine motor coordination underlies the child's overall level of cognitive and academic functioning (Decker et al., 2011). As defined here and elsewhere, fine motor coordination refers to small muscle movements but not the integration of these muscle movements with other input, such as visual–spatial information, from the environment (Carlson et al., 2013; Korkman et al., 1998).

Developmental course. Fine motor coordination develops rapidly early in childhood, following a roughly logarithmic trajectory, and continues to develop into early adulthood before declining in late adulthood (Beery & Beery, 2004). Fine motor coordination is an integral part of the school day in early childhood, with more than a third of the preschool day and more than 40% of the kindergarten day requiring fine motor skills (Marr, Cermak, Cohn, & Henderson, 2003). Children rely on fine motor coordination for a wide range of tasks, such as reaching for an object or tying their shoes, or holding and manipulating writing utensils.

Relevance for mathematics. Fine motor coordination is fundamental for interacting with and understanding the physical world, and in turn, developing mathematically relevant skills, such as understanding concepts of shape, space, and numeracy (Newcombe & Frick, 2010). For instance, children with strong, compared to those with weak, fine motor coordination may be able to manipulate objects more efficiently, thereby increasing their understanding of spatial relationships and their ability to mentally represent objects (Luo et al., 2007). Thus, automaticity in basic coordination skills may provide an advantage in learning mathematics by allowing attentional resources to be directed toward learning higher order concepts rather than toward control of motor movements (LaBerge & Samuels, 1974).

Research suggests that rudimentary fine motor coordination may not directly contribute to mathematics skills but rather may do so indirectly through other more complex skills, such as visuomotor integration. For instance, Sortor and Kulp (2003) found that fine motor coordination was no longer significantly related to mathematics after controlling for attention and visuomotor integration in their sample of second through fourth graders. Similarly, fine motor coordination was not associated with mathematics achievement after controlling for visuomotor integration in Carlson et al. (2013). Taken together, these studies suggest that,

although fine motor coordination is important for providing immediate access to mathematical learning through interacting with the environment (Newcombe & Frick, 2010), additional development beyond a certain skill level may not directly contribute to mathematics performance. Instead, fine motor coordination may be prerequisite for other higher order cognitive processes, such as visuomotor integration and attention, which are more directly important for mathematics.

Summary

Motor and cognitive development are dynamically interrelated from infancy through early childhood, with theory and evidence supporting notions of both reciprocal relations and dependency among motor and cognitive skills. Reciprocity does not necessarily continue indefinitely nor does dependency in the form of automaticity in rudimentary skills supporting development of more complex skills. Visuomotor integration, attention, and fine motor coordination are specific skills, which may share such complex relations with each other, as well as with mathematics skills, as they develop in early childhood. However, the dynamic relations among all of these constructs are not well understood.

Present Study

Using an ACL approach, this study examined how visuomotor integration, attention, and fine motor coordination were related to each other and to mathematics skills in a diverse sample of children across 2 years of early elementary school. We sought to address the following question: What are the longitudinal relations among visuomotor integration, attention, fine motor coordination, and mathematics skills? Although these analyses were exploratory, we did have some expectations, and these were shaped by the reciprocity and automaticity accounts of relations between motor and cognitive development. Generally speaking, more reciprocal effects were expected in early childhood than later on, given the gradual differentiation of cognitive processes and supporting brain structures over the course of development (Johnson, 2001). However, we also expected differences in relations to mathematics depending on the cognitive process in question.

For instance, we expected visuomotor integration to significantly contribute to mathematics skills across all time points (Decker et al., 2011), and we expected these contributions to be stronger than those of fine motor coordination but not necessarily those of attention (Carlson et al., 2013; Sortor & Kulp, 2003). Second, we expected a sustained contribution of attention to mathematics skills over time (Blair et al., 2008). Third, we expected that the direct contribution of fine motor coordination to mathematics skills might weaken over time. Furthermore, we predicted fine motor coordination might eventually only indirectly contribute to mathematics skills through visuomotor integration (i.e., mediation), as fine motor coordination becomes more automated with practice and maturation (Carlson et al., 2013). Finally, we expected bidirectional associations among mathematics, attention, and visuomotor integration over time (Clements et al., 2016; Fuhs et al., 2014).

Method

The present study, which is observational by design, uses data from three experimental studies that tested the effects of an after-school fine motor skills intervention on young children's cognitive and academic skills. Over 3 years, children were recruited from eight schools across two different geographic sites (see descriptive statistics by site in Tables S1 and S2). Children from the first site were recruited in Year 1 from one rural and four urban schools in a mid-Atlantic state, and children from the second site were recruited in Years 2 and 3 from three urban schools in a southeastern state serving extremely low-income families. Following recruitment, all children then participated in the intervention (or control condition) for 1 year and also had a follow-up assessment 1 year after the intervention period ended. Thus, the overall study and data collection period spanned 3 consecutive years from January 2010 to May 2013, and each child's study participation spanned 2 consecutive school years.

Because the intervention was under development, the treatment groups' experiences differed significantly from 1 year to the next, in terms of activities, schedule, and dose. Of note, the intervention delivered to children recruited in Year 2 was the only intervention that produced significant effects on attention and visuomotor integration, but not overall mathematics skills, for children in the treatment group (Grissmer et al., 2013). This means that only 17% (45 of 254) of children were assigned to a treatment condition in which the intervention had positive effects. Furthermore, we expected the

intervention to generally improve children's motor and cognitive processes over a single school year—not to change how these processes related with each other and mathematics achievement over multiple years (the foci of the present study). Still, to control for the potential influence of exposure to the intervention on children's development of motor and cognitive processes and on mathematics skills, we included whether children received the intervention as a covariate in all analyses. Furthermore, we performed sensitivity analyses to confirm our results were not driven by intervention status.

Participants

One hundred thirty-five kindergarten students were recruited to participate in the study, of which 46% were in the treatment group, 50% were in the control group, and 4% did not consent to randomization and, thus, were not randomized and did not receive treatment. One hundred nineteen first-grade students were recruited, of which 52% were in the treatment group, 44% were in the control group, and 4% were not randomized and did not receive treatment. For ease of communication, we will henceforth refer to the children who began the study as kindergarteners as the "kindergarten cohort" and children who began as first graders as the "first-grade cohort," even though each of these "cohorts" in reality comprises children from three separately recruited groups. All kindergarten (34% from Site 1) and first-grade (39% from Site 1) students at both sites were eligible to participate, except those with severe disabilities that would prevent completion of the assessment battery.

Table 1 provides descriptive statistics for our sample by cohort. For the kindergarten cohort (50% male), children ranged in age from 5.0 to 6.8 years (M = 5.6 years, SD = 0.37) at the beginning of kindergarten. In the first-grade cohort, children (54% male) ranged in age from 6.0 to 7.9 years (M = 6.7 years, SD = 0.43) at the beginning of first grade. Overall, families reported children's ethnicity and race as 71% African American or Black, 26% Caucasian or White, and 3% other (Hispanic or Latino, Asian, or multirace). In both cohorts, most children (71%) were eligible for lunch subsidy and had attended preschool (84%).

Longitudinal Design and Procedure

Data for the current observational study were from three assessment time points across two school years, with the pretest assessments collected before the intervention at the beginning of the academic year and posttest assessments collected toward the end of the academic year. A second round of posttest assessments was collected approximately 1 year after the first posttest. Thus, data for the kindergarten cohort were collected during the first half of the kindergarten year (Time 1), at the end of kindergarten (Time 2) and at the end of first

Table 1
Descriptive Statistics by Grade

	Child age (years)	Fine motor coordination			Attention			Visuomotor integration			Mathematics skills		
		Time 1	Time 2	Time 3	Time 1	Time 2	Time 3	Time 1	Time 2	Time 3	Time 1	Time 2	Time 3
Kindergarten													
n	134	130	127	91	126	124	90	133	128	91	135	129	91
% Missing	1	4	6	33	7	8	33	1	5	33	0	4	33
M	5.61	10.83	15	19.96	8.23	10.31	14.13	33.84	39.5	44.36	14.44	20.72	28.38
SD	0.37	6.2	7.56	8.41	4.34	4.75	5.5	8.97	7.76	7.53	7.58	8.17	10.01
Minimum	4.97	1	1	3	1	1	3	5	18	25	1	2	7
Maximum	6.84	32	34	36	18	21	30	63	61	61	49	44	51
First grade													
n	119	116	112	75	114	112	75	116	112	75	119	112	94
% Missing	0	3	6	37	4	6	37	3	6	37	0	6	21
M	6.7	16.26	20.49	22.71	10.52	14.65	16.95	41.18	45.13	48.87	23.17	32.65	40.59
SD	0.43	7.14	7.66	8.23	4.8	5.21	6.13	7.76	7.32	7.01	10.46	11.4	12.47
Minimum	6	2	3	3	1	5	4	22	30	33	4	12	13
Maximum	7.89	32	40	38	26	29	34	56	69	65	53	64	72

Note Time 1 = beginning of kindergarten (kindergarten cohort) or first grade (first-grade cohort); Time 2 = end of kindergarten (kindergarten cohort) or first grade (first-grade cohort); Time 3 = end of first grade (kindergarten cohort) or second grade (first-grade cohort).

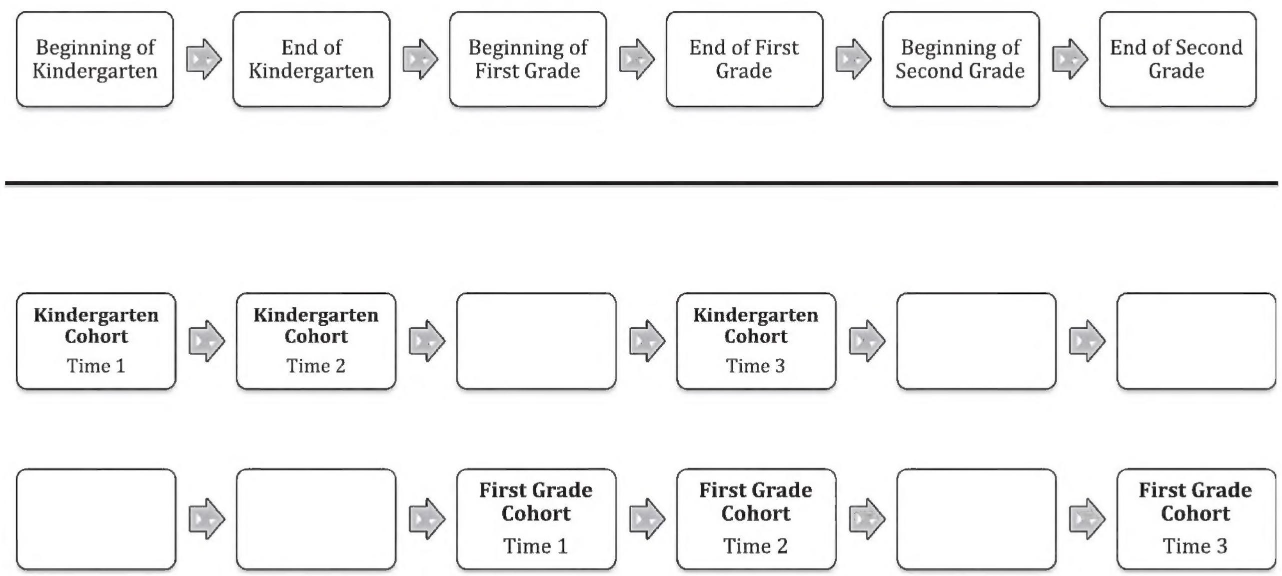

Figure 1. Data collection timeline for the kindergarten and first-grade cohorts. The kindergarten cohort data were collected at the beginning of kindergarten (Time 1), end of kindergarten (Time 2), and end of first grade (Time 3). The first-grade cohort data were collected at the beginning of first grade (Time 1), end of first grade (Time 2), and end of second grade (Time 3). Due to these data collection constraints, with only one time point overlapping (end of first grade) between the two cohorts, cross-lagged models were run separately for the kindergarten and first-grade cohorts.

grade (Time 3); data for the first-grade cohort were collected during the first half of the first-grade year (Time 1), at the end of first grade (Time 2) and at the end of second grade (Time 3). See Figure 1 for the time points and corresponding grade levels for each cohort. Trained researchers individually administered assessments in a quiet area of the school or classroom. At each time point, assessments took place in two 45- to 60-min sessions over 2 days.

Measures

The NEuroPSYchological assessment battery (NEPSY; Korkman et al., 1998) was used to measure children's motor and cognitive processes. The NEPSY is a comprehensive, reliable, direct neuropsychological assessment for children 3–12 years of age. The NEPSY comprises subtests organized into five functional domains, which have moderately high internal consistency, with coefficients ranging from .79 to .90 depending on the age and domain (see Korkman et al., 1998 for more detailed psychometric information). For the present study, one subtest from each of three of the five domains (visuospatial processing, attention/executive functions, sensorimotor functions)—*design copy*, *visual attention*, and *visuomotor precision*—were used to assess children's visuomotor integration, attention, and fine motor coordination, respectively. Except where noted, study reliabilities, which we report for each measure, were similar to published reliabilities.

Visuomotor Integration

The *design copy* subtest falls under the visuospatial processing domain and requires integrating visuospatial and motor coordination skills. Children copied increasingly complex two-dimensional figures using pencil and paper. Each design was scored from 0 to 4 points, for a total of 72 possible points on 18 items. Test–retest reliability for the design copy subtest was r = .60–.72 for the kindergarten cohort and r = .60–.74 for the first-grade cohort.

Attention

The *visual attention* subtest is part of the attention/executive functions domain and assesses the speed and accuracy with which a child is able to focus selectively on and maintain attention to visual targets as they scan an array and locate a target. Children were asked to select a target picture (Trial 1) or pictures (Trial 2) out of a large array of similar pictures presented on a worksheet-style booklet. Accuracy scores were determined by subtracting the number of commission errors (number of nontarget pictures marked) from the number of

correctly identified target pictures. Time scores were calculated using the sum of time taken for both trials (maximum 180 s per trial). Final raw scores were based on both time and accuracy. For the current sample, test–retest reliability for the visual attention subscale was $r = .40–.57$ for the kindergarten cohort and $r = .59–.72$ for the first-grade cohort.

Fine Motor Coordination

The *visuomotor precision* subtest is part of the sensorimotor functions domain and assesses speed and accuracy of eye–hand coordination. For each of two items, children were asked to draw a line inside a track within a time limit (180 s per item). The maximum time score is 360 s, and the maximum error (accuracy) score for ages 5–12 is 307. The total raw score considers both the speed and accuracy scores. The test–retest reliability in the current sample was $r = .39–.53$ for the kindergarten cohort and $r = .37–.48$ for the first-grade cohort. These are lower than the published test–retest reliability for 5- to 6-year-olds ($r = .78$) but higher than that for 7- to 8-year-olds ($r = .23$; Korkman et al., 1998). It is noteworthy that time between tests for published reliabilities was between 2 and 10 weeks, whereas the time between tests for this study ranged from 4 months to a year, which may explain why reliability was somewhat lower than expected for younger children.

Mathematics Skills

Children's mathematics skills were assessed using a composite of three subscales of the KeyMath-3 Diagnostic Assessment, a comprehensive and reliable assessment for children 4½–21 years of age (Connolly, 2008). *Numeration* measures children's number awareness and number sense (e.g., "add 3 dots to make 5"). *Geometry* measures children's ability to analyze two- and three-dimensional shapes, as well as their understanding of spatial relationships and reasoning (e.g., "point to shapes: circle, square"). *Measurement* measures children's ability to compare objects on a variety of attributes (e.g., "point to tallest & shortest plants"). The three subscales had high intercorrelations in our sample ($r = .77–.91$); therefore, we used the average of the three subscale scores to create a composite score at each of the three time points. For the current sample, composite score test–retest reliabilities were $r = .74–.82$ for the kindergarten cohort and $r = .84–.89$ for the first-grade cohort.

Covariates

Covariates included child's age in years, gender (0 = female, 1 = male), study site (0 = Site 1, 1 = Site 2), lunch subsidy status (0 = not eligible, 1 = eligible), and treatment group status (0 = control or nonrandomized group, 1 = treatment group).

Analytic Approach

All analyses, including descriptive statistics, correlations, and autoregressive cross-lag analyses, were conducted using Stata 14.1 (StataCorp, 2015).

Autoregressive, Cross-Lagged Models

An ACL model was fit to the longitudinal data for each cohort. Based on a structural equation modeling framework, the ACL model simultaneously tested multiple predictive associations among the three motor and cognitive processes and mathematics skills across three time points. Data collection for this study took place with relatively constant time lag among participants for all variables within each cohort.

As previously stated, we expected the associations among the processes to change depending on the age of the child. Given the two age groups included in this study, we acknowledge that an accelerated longitudinal design would appear nicely suited to accommodate the aim of this article (see Miyazaki & Raudenbush, 2000). Such a design would test a single model including the data from both cohorts; this initially appears possible, because both cohorts were tested at a common time point (i.e., Time 3 for kindergarteners and Time 2 for first graders, which both occurred at the end of first grade). However, this was the only time point shared between cohorts (see Figure 1), and experts argue that, in an accelerated longitudinal design, at least two measurement occasions should overlap (Little, 2013). Furthermore, a single model would have required modeling all nonshared time points (a majority) as latent variables, for which each would be missing data at a rate of about 50%. This inconsistency is an artifact of the design of the larger intervention study from which the data for the present study originate. Hence, the models for kindergarten and first-grade cohorts were examined separately, but results are interpreted in terms of dynamic relations throughout the course of development from the beginning of kindergarten through the end of second grade.

Although the ACL model tests linear relations between pairs of constructs between two time points, we did not constrain growth trajectories of the individual constructs to be linear. In addition, any path between any two variables across time points was estimated and unconstrained, and covariances between the residuals of each variable were allowed within each time point for all time points. The model was fully recursive in that paths directed only forward in time, and any variable assessed at an earlier point in time was used to predict all later variables. The fit of the model for each cohort was assessed using the following criteria: Tucker–Lewis index and comparative fit index greater than 0.95 and the root mean square error of approximation less than or equal to 0.06 (Hu & Bentler, 1998).

To test potential hypothesized mediation effects, RMediation (Tofighi & MacKinnon, 2011) was used to conduct the empirical *M* test (i.e., asymmetrical confidence interval). This method produces more accurate confidence limits compared to other methods that assume the product between two normally distributed variables is, itself, normally distributed (MacKinnon, Fritz, Williams, & Lockwood, 2007). The mediation effect is considered significant if the confidence interval does not include zero.

Missing Data

Information on missing data is available in Table 1 with the greatest extent of missing data at the latest time points (Enders, 2010). Of the 254 participants, a total of 150 (59%; 78 kindergarteners and 72 first graders) had complete data across all study outcome variables at every time point. The design of the larger intervention study dictated that the third time point for approximately one-third of the first-grade cohort (22 participants; 9% of the entire sample) was not administered any of the cognitive measures at Time 3. Thus, study design explains about 25% of the missing data for Time 3; the rest of the missing data is due to participant attrition.

Attrition can lead to data that are not missing at random, which can bias parameter estimates, especially when traditional methods (e.g., listwise deletion) are used (Enders, 2010). Selectivity effects are of particular concern. Missing data analyses revealed more missing data for African American children and those eligible for free–reduced lunch. These differences were no longer significant after accounting for site, however, because demographic characteristics were significantly different across sites and a large portion of the missingness was explained by study design and site (as described earlier; see Tables S1 and S2 for site-specific descriptives). Full information maximum likelihood estimation method was used to account for the missing data and to use all available information to obtain more efficient, less-biased estimates than deletion methods (Enders, 2010).

Results

Table 1 shows means, standard deviations, and ranges for kindergarten and first-grade cohorts for all analytic variables. In general, performance improved on all four measures across the three time points for both kindergarten and first-grade cohorts. Zero-order correlations among all variables were also examined and showed that, across cohorts and time points, chronological age was positively related to all constructs (r = .09–.46; see Table S3). Thus, partial correlations controlling for differences in chronological age are presented in Table 2. Controlling for differences in chronological age did not substantially affect the overall pattern of associations among the variables, which rules out the possibility that age was an exclusive explanation for these zero-order correlations.

For both cohorts and at most time points, boys and children who qualified for free–reduced lunch had significantly lower scores on all constructs than girls and those not qualifying for free–reduced lunch, respectively. In addition, across grades and time points, all target constructs exhibited within-construct stability, and all correlations among these were positive. Correlations among visuomotor integration, attention, and fine motor coordination at each time point were low to moderate in magnitude, suggesting both relatedness and distinctness among these constructs over time.

Developmental Associations Among Motor and Cognitive Processes and Mathematics

Figures 2 and 3 present results for the model that tested the stability and transactional relations among visuomotor integration, attention, fine motor coordination, and mathematics skills in the kindergarten and first-grade cohorts, respectively. Covariates were age, gender, lunch subsidy status, site, and treatment condition. All fit statistics were well within the accepted ranges for indicating good fit for both cohorts (Hu & Bentler, 1998).

Table 2
Partial Correlations Controlling for Chronological Age for All Variables Included in the Analyses for Kindergarteners (n = *135; Bottom Half of Table) and First Graders* (n = *119; Top Half)*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Gender	—	.034	−.021	−.064	−.103	−.330**	−.158	−.049	−.006	−.101	−.145	−.192*	.056	−.081	−.065	.000
2. FORL	.099	—	−.049	.547**	−.261**	−.261**	−.103	−.179	−.192*	−.241*	−.271**	−.235*	−.245*	−.475**	−.401**	−.309**
3. Treatment	.066	−.056	—	−.010	−.037	.060	−.189	−.010	.094	.127	.054	.182	.034	−.001	−.011	.069
4. Site	.019	.783**	.013	—	−.099	−.168	−.321**	−.364**	−.380**	−.506**	−.268**	−.250**	−.480**	−.622**	−.532**	−.530**
5. FMC T1	−.185*	−.302**	−.044	−.301**	—	.370**	.361**	.192*	.220*	.205	.311**	.264**	.186	.236*	.230*	.208*
6. FMC T2	−.226*	−.311**	.071	−.305**	.530**	—	.480**	.173	.264**	.231*	.230*	.365**	.131	.176	.145	.035
7. FMC T3	−.161	−.193	−.194	−.180	.490**	.392**	—	.315**	.279*	.318**	.262*	.257*	.294*	.237*	.157	.151
8. Attention T1	−.155	−.145	−.025	−.256*	.129	.126	.051	—	.516**	.515**	.409**	.286**	.316**	.475**	.358**	.377**
9. Attention T2	−.078	−.265**	−.003	−.205**	.124	.212*	.116	.365**	—	.658**	.359**	.343**	.364**	.398**	.338**	.474**
10. Attention T3	−.115	−.404**	.060	−.465**	.148	.340**	.115	.369**	.535**	—	.400**	.419**	.392**	.497**	.412**	.491**
11. VMI T1	−.222*	−.294**	−.021	−.373**	.377**	.471**	.313**	.146	.343**	.342**	—	.717**	.591**	.567**	.612**	.580**
12. VMI T2	−.145	−.321**	.041	−.322**	.434**	.471**	.479**	.148	.327**	.378**	.688**	—	.675**	.529**	.588**	.579**
13. VMI T3	−.308**	−.306**	.071	−.276**	.360**	.396**	.403**	.256*	.408**	.374**	.576**	.706**	—	.541**	.561**	.669**
14. Math T1	−.080	−.574**	−.015	−.552**	.250**	.382**	.175	.145	.413**	.492**	.533**	.511**	.417**	—	.891**	.834**
15. Math T2	−.068	−.558**	−.019	−.589**	.314**	.383**	.210*	.261**	.375**	.423**	.514**	.519**	.525**	.796**	—	.871**
16. Math T3	−.212	−.571**	.063	−.540**	.202	.306*	.137	.299*	.445**	.536**	.575**	.531**	.448**	.727**	.801**	—

Note Gender (male = 1). FORL = free/reduced lunch status (yes = 1); Treatment = treatment condition (0 = control, 1 = treatment); FMC = fine motor coordination; VMI = visuo-motor integration; Math = mathematics skills; T1 (Time 1) = beginning of kindergarten (kindergarten cohort) or first grade (first-grade cohort); T2 (Time 2) = end of kindergarten (kindergarten cohort) or first grade (first-grade cohort); T3 (Time 3) = end of first grade (kindergarten cohort) or second grade (first-grade cohort). $*p < .05$. $**p < .01$.

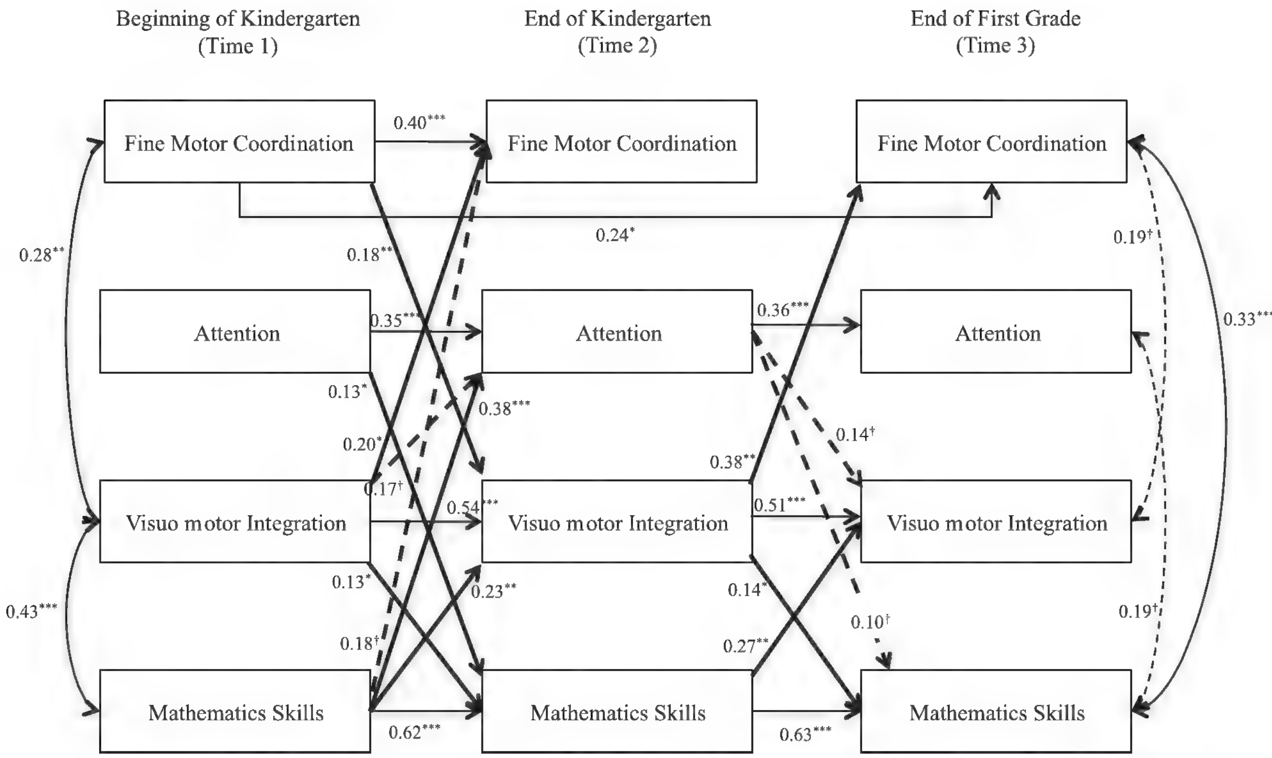

Figure 2. Autoregressive, cross-lag model depicting longitudinal, reciprocal relations between three cognitive processes (visuomotor integration, attention, and fine motor coordination) and mathematics skills across 2 school years from beginning of kindergarten (Time 1) to end of kindergarten (Time 2) and end of first grade (Time 3), controlling for child's age, gender, lunch subsidy status, site, and treatment condition (full model; covariates not shown). All possible paths were included in the model. This model fit the data well, $\chi^2(12) = 10.07$, $p = .61$, $N = 135$; comparative fit index (CFI) = 1.00, root mean square error of approximation (RMSEA) = 0.00, Tucker Lewis index (TLI) = 1.025. Solid lines represent significant relations, dashed lines represent marginally significant relations ($p < .10$), and nonsignificant relations are not shown. Bold lines represent significant cross-lag paths. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Summary of Longitudinal Associations

Consistent with expectations, we observed transactional relations among visuomotor integration, attention, fine motor coordination, and mathematics skills in kindergarten, with the number of significant relations and strength of associations among the four constructs diminishing in first and second grades. Additionally, all four constructs showed stability over time, with positive and statistically significant autoregressive loadings between time points (βs = .35–.63 in the kindergarten cohort, βs = .29 .91 in the first-grade cohort, $ps < .05$), with the exception of fine motor coordination between Time 2 and Time 3 for the kindergarten cohort. Furthermore, as expected, contributions of visuomotor integration, attention, and fine motor coordination to mathematics changed over time.

Visuomotor integration. Visuomotor integration and mathematics skills were positively and reciprocally related. Specifically, for the kindergarten cohort (Figure 2), the paths from visuomotor integration to mathematics skills were consistently significant and positive ($\beta = .13$ from Time 1 to Time 2, $\beta = .14$ from Time 2 to Time 3, $ps < .001$), as were the paths from mathematics skills to visuomotor integration ($\beta = .23$ and $\beta = .27$, respectively, $ps < .05$). This means that change over time in visuomotor integration predicted change over time in mathematics skills, and vice versa. Similarly, for the first-grade cohort (Figure 3), visuomotor integration positively contributed to mathematics skills from Time 1 to Time 2 ($\beta = .21$, $p < .001$) and vice versa ($\beta = .26$, $p < .05$). However, this reciprocal relation diminished between Time 2 and Time 3, across which only visuomotor integration contributed to mathematics skills ($\beta = .17$, $p < .01$) but not vice versa.

Attention. Attention contributed to mathematics skills across both time intervals for both the kindergarten cohort ($\beta = .13$ and $\beta = .10$, respectively, $ps < .10$) and the first-grade cohort ($\beta = -.15$ and $\beta = .13$, respectively, $ps < .05$). For the kindergarten cohort only, there was also a significant contribution of mathematics skills to attention ($\beta = .38$, $p < .001$) between Time 1 and Time 2, suggesting a

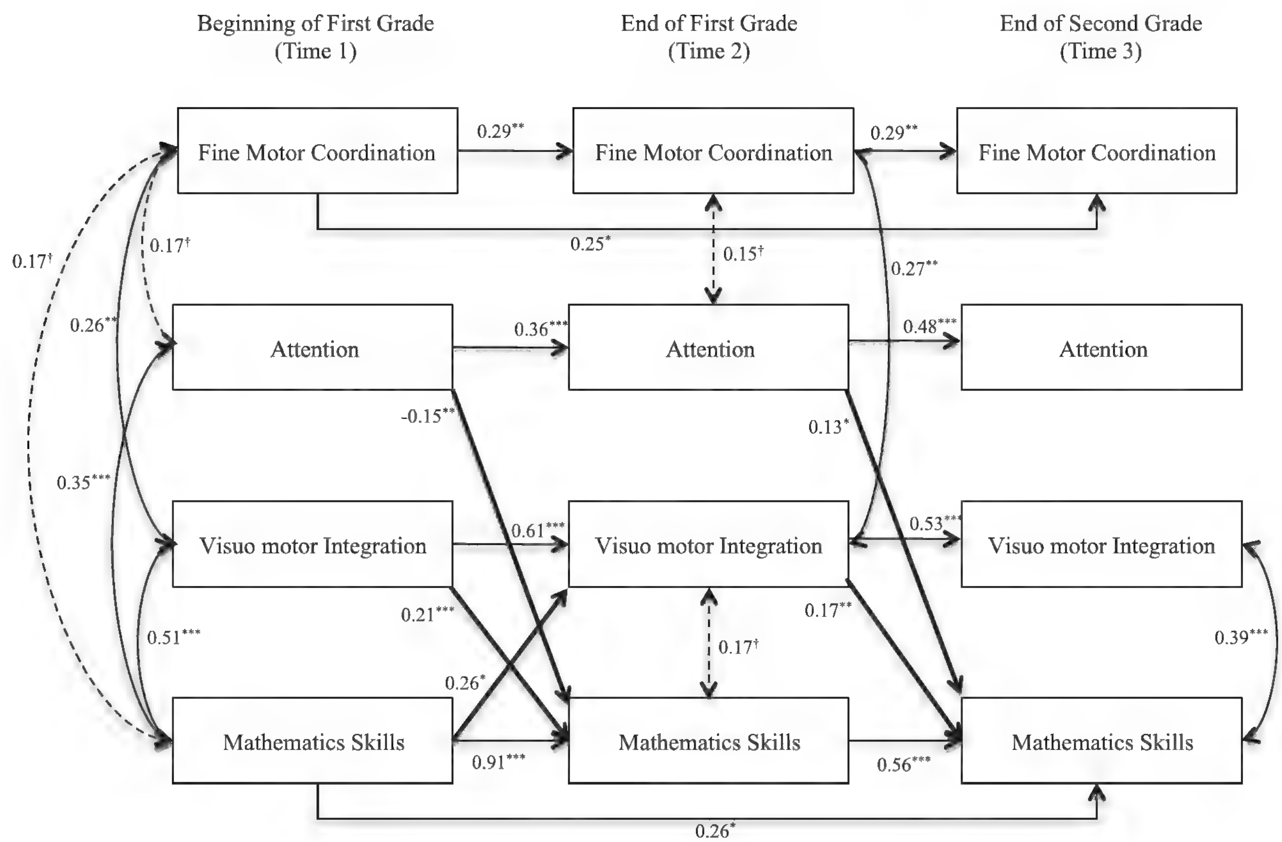

Figure 3. Autoregressive, cross-lag model depicting longitudinal, reciprocal relations between three cognitive processes (visuomotor integration, attention, and fine motor coordination) and mathematics skills across 2 school years from beginning of first grade (Time 1) to end of first grade (Time 2) and end of second grade (Time 3), controlling for child's age, gender, lunch subsidy status, site, and treatment condition (full model; covariates not shown). All possible paths were included in the model. This model fit the data well, $\chi^2(12) = 8.02$, $p = .78$, $N = 119$; comparative fit index (CFI) = 1.00, root mean square error of approximation (RMSEA) = 0.00, Tucker Lewis index (TLI) = 1.046. Solid lines represent significant relations, dashed lines represent marginally significant relations ($p < .10$), and nonsignificant relations are not shown. Bold lines represent significant cross-lag paths. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

reciprocal relation between these two constructs in the kindergarten year, which diminished thereafter.

The negative path loading from attention to mathematics skills from Time 1 to Time 2 in the first-grade cohort was in the unexpected direction—despite strong positive correlations between attention and mathematics at those times points. A suppressor effect occurs when the direction of the beta weight changes when additional predictors are added (Burkholder & Harlow, 2003). Suppression likely occurred here because of multicollinearity between attention, visuomotor integration, and mathematics skills at Time 1, as well as mathematics skills at Time 2. Multicollinearity is particularly evident in the loading from mathematics skills at Time 1 to mathematics skills at Time 2 ($\beta = .91$, $p < .001$), which leaves very little variance in Time 2 mathematics skills to be explained by other constructs. This loading is much larger than any other loading observed in the model and is about 50% larger than other loadings representing stability in mathematics skills in both cohorts. In a simple follow-up regression analysis in the first-grade cohort, attention at Time 1 positively and significantly predicted mathematics skills at Time 2 ($\beta = .43$, $p < .001$). However, when mathematics skills at Time 1 was included in the regression, the association was still significant but became negative ($\beta = -.12$, $p < .05$).

The coefficient in the kindergarten cohort from attention to mathematics skills over the most closely corresponding time interval (i.e., Time 2 to Time 3, end of kindergarten to the end of first grade) is positive. However, there was less collinearity among the constructs in the kindergarten cohort across this time interval compared to the first-grade cohort, as just described, which may provide one explanation as to why multicollinearity affected the first-grade coefficient but not the kindergarten coefficient. Thus, we acknowledge that this multicollinearity warrants

caution in any substantive interpretation of the loading from attention at Time 1 to mathematics at Time 2 for the first-grade cohort. Nonetheless, given that the extent of multicollinearity between these constructs is much greater than for any other constructs and time intervals in the model and in both cohorts, we do not suspect that such caution is needed in the interpretation of other loadings in the model.

Fine motor coordination. For both cohorts, fine motor coordination did not directly predict mathematics skills at any of the time points, nor did it predict mathematics skills through contributions to other processes in first grade. For the kindergarten cohort only, however, fine motor coordination at Time 1 contributed significantly to visuomotor integration at Time 2 ($\beta = .18$, $p < .01$), which was, in turn, significantly related to mathematics skills at Time 3 ($\beta = .14$, $p < .05$). In other words, fine motor coordination at the beginning of kindergarten indirectly contributed to mathematics skills at the end of first grade through its effect on visuomotor integration at the end of kindergarten (95% CI = [0.001, 0.016], $\beta = .025$, $SE = .016$). The total effect, which includes both indirect and direct effects, of fine motor coordination at Time 1 on mathematics skills at Time 3 was $\beta = .05$, and the direct mediated effect was $\beta = -.01$. Thus, visuomotor integration at Time 2 mediated 0.025/0.05 = 50% of the effect between fine motor coordination at Time 1 and math at Time 3.

Covariates

In general, effects of covariates on outcomes at Time 1, when significant, were in the expected direction, with children qualifying for free reduced lunch (βs ranged from $-.18$ to $-.35$) and those from Site 2 (βs ranged from $-.28$ to $-.55$) having lower scores on most measures. Also, boys scored lower than girls in attention ($\beta = -.16$) and visuomotor integration ($\beta = -.20$). Effects of covariates on outcomes at Time 2 were not significant except for gender on fine motor coordination ($\beta = -.30$, $p < .01$). Because Time 2 coincided with the end of the intervention, the lack of any significant effects of treatment condition at this time point is consistent with our presumption that the intervention did not significantly alter children's skills in the sample.

At Time 3, treatment condition was negatively related to fine motor coordination for both kindergarten and first-grade cohorts (βs = $-.22$, $-.25$, respectively, $p < .05$); this is in the opposite direction from any reported treatment effects and on a measure that was not affected by the intervention (Grissmer et al., 2013). Yet, treatment condition was not significantly correlated with any of the variables included in the study (see Table 2). Moreover, in a simple follow-up regression analysis, treatment did not significantly predict fine motor coordination at Time 3 for either of the cohorts. Furthermore, lunch subsidy status was positively related to fine motor coordination among the first-grade cohort ($\beta = .25$, $p < .05$); site was negatively related to fine motor coordination ($\beta = -.41$, $p < .01$) and attention ($\beta = -.31$, $p < .01$) in the first-grade cohort. The positive relation between lunch subsidy status and fine motor coordination is in the unexpected direction but may be due to a suppression effect of site, because children from Site 2 were more likely to qualify for lunch subsidy status than Site 2, and site was also controlled for in these analyses.

Sensitivity Analyses

We were interested in whether our results were sensitive to participation in the three interventions, which differed by site, recruitment year, and impacts. Due to small sample size, we were unable to include a separate variable for each of the three interventions. However, we ran sensitivity analyses including site and treatment group (control vs. treatment), as well as an interaction between intervention at Year 2 and treatment. These analyses were of particular interest given that the intervention in Year 2 was the only one that produced significant condition differences. Including the interaction term did not change the path coefficients in any way. For completeness, we also ran similar separate analyses including intervention at Year 1 and treatment and intervention at Year 3 and treatment, and these interaction terms did not change the results either. Thus, we are confident that our results are not dependent on or driven by children's participation in the interventions offered.

Our observation of cross-lagged relationships between attention and mathematics skills in the kindergarten year is in contrast with other studies suggesting such bidirectional relationships do not occur beyond the prekindergarten year (Fuhs et al., 2014). In order to determine whether this might be due to the relative disadvantage of our sample compared to Fuhs et al. (2014), we performed follow-up analyses testing the hypothesis that perhaps the cross-lag relations observed were due to the Site 2 sample, which was more disadvantaged than the Site 1 sample. In these analyses, we ran our kindergarten cohort model including an interaction effect between site and attention at Time 1 on mathematics skills at Time 2, as well as an interaction effect

between site and mathematics skills at Time 1 on attention at Time 2. Results were mixed, such that the interaction terms did not significantly predict outcomes in these analyses, suggesting the loadings for these two sites did not significantly differ. However, the path from mathematics skills at Time 1 to attention at Time 2 was only statistically significant when Site 2 was the reference group, which could either suggest that a larger sample from Site 1 would also not have produced significant cross-lag relationships or could simply be due to sample size.

Discussion

We examined dynamic relations among visuomotor integration, attention, fine motor coordination, and mathematics skills in a diverse sample of kindergarten and first-grade children across 2 academic years. This study extends existing work by demonstrating a course of differentiation among these theoretically and empirically related skills, with more interrelations among processes observed in kindergarten than in first and second grades. This finding is consistent with theory suggesting that children's cognitive processes differentiate or "functionally specialize" as they develop (Johnson, 2001). In general, findings contribute to a growing literature linking early elementary children's motor and cognitive processes with their mathematics skills through specific pathways. Furthermore, many of this study's findings are consistent with either the reciprocity and automaticity accounts of relations between motor and cognitive skills.

Visuomotor Integration and Mathematics Skills Are Reciprocally Related

Even after controlling for attention and fine motor coordination, visuomotor integration and mathematics skills exhibited ongoing reciprocity, with the exception of the time period between the end of first grade to the end of second grade for the first-grade cohort. The perceptual, motor, and cognitive skills necessary for visuomotor integration task performance contribute to basic learning skills associated with mathematics skills, including attending to and accurately perceiving numbers, visually discriminating similar symbols (e.g., "6" and "9") or diagrams presented on the board, visually maintaining one's place on the page or board, and integrating these abilities with fine motor coordination to form and reproduce the numbers accurately using paper and pencil (Sortor & Kulp, 2003).

In addition, visuomotor integration and mathematics skills may be fostered through common activities. For instance, mathematics instruction in kindergarten often involves manipulating physical objects, and these hands-on instructional techniques appear to be particularly effective in kindergarten (Guarino, Dieterle, Bargagliotti, & Mason, 2013). At the same time, developments in mathematics skills may, in turn, support developments in visuomotor integration, because these activities provide opportunities for children to practice integrating multiple processes. The fact that mathematics skills at Time 2 was no longer predictive of visuomotor integration at Time 3 in the first-grade cohort may be explained by the fact that visuomotor integration is more useful for solving arithmetic problems, such as addition and subtraction (Rourke & Finlayson, 1978), but not in fact retrieval (Fletcher, 1985). Thus, our finding is reasonable as the mathematics skills measure emphasized numeration problems and mathematical concepts that, by the end of second grade, may involve more fact retrieval than in first grade or kindergarten.

Attention Consistently Contributes to Development in Mathematics Skills

Our study also demonstrated that development in attention over time contributes to increased mathematics skills across both kindergarten and first grade, even after controlling for visuomotor integration and fine motor coordination. This pattern is consistent with several similar studies among 4- to 6-year-olds (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Fuhs et al., 2014; Welsh et al., 2010). More specifically, strong performance on the attention task in this study indicates that a child can inhibit distracting stimuli while simultaneously attending to task-relevant stimuli (Klenberg et al., 2001). These processes may be particularly relevant to mathematics learning in the early elementary years (Geary, 2013), which requires identifying and understanding the task goal, knowing where and when to attend for important information, sustaining attention to reach the goal, and carrying out a sequence of behaviors that will allow for efficient completion (Assel et al., 2003). For instance, compared to children who score low on the attention task, those who score higher on attention may be able to more quickly understand how to count objects (a rule-based process), which then allows more attentional resources to be devoted to learning complex skills, such as problem solving (Gersten & Chard, 1999). At the same time, poor counting skills

may mean more counting errors, thereby strengthening the association between incorrect answers and the specific counting task, which may lead to difficulties in suppressing the retrieval of irrelevant associations (e.g., Aunola et al., 2004).

In the kindergarten year only, mathematics skills made unique, reciprocal contributions to the development of attention, which is consistent with our expectation that attention and mathematics skills might exhibit some degree of reciprocity but perhaps not consistently over time. This likely indicates that attention is required not only for learning mathematics early in formal schooling but also that mathematics assessments are strong indicators of attention. This is in slight contrast to previous work finding bidirectional associations between mathematics skills and EF in the prekindergarten (4-year-old) year but not in the kindergarten year (Fuhs et al., 2014). However, our sample was more disadvantaged overall, and it may be that experience is driving the transient reciprocity rather than age. Indeed, our sensitivity analyses testing this hypothesis provided suggestive evidence that this may be the case. More advantaged children have key learning experiences earlier, which may provide them with skills that are at similar levels with older, less advantaged children; thus, our results may complement, rather than contradict, previous findings.

An alternative, but not mutually exclusive, explanation for our observation of a cross-lag relationship between attention and mathematics skills during kindergarten may be differences in how attention and mathematics skills were studied here compared to in Fuhs et al. (2014). Our study included a specific task tapping a specific aspect of attention and a composite score for mathematics skill measuring children's general mathematics skills (Connolly, 2008). It may be that a specific measure of attention may be more strongly linked to general mathematics skills in kindergarten than an aggregated measure of EF is to specific types of mathematics skills requiring complex thinking (i.e., problem solving); the latter of which were the focus of the study conducted by Fuhs et al. (2014).

Fine Motor Coordination Indirectly Relates to Mathematics Skills

For the kindergarten cohort, children's fine motor coordination and their mathematics skills were indirectly linked through visuomotor integration over the course of the kindergarten year. This complements previous studies (e.g., Carlson et al., 2013; Grissmer et al., 2010) and other work highlighting that basic motor functions precede the development of more complex functions, which in turn, affect academic outcomes (Klenberg et al., 2001). In early childhood, having strong fine motor coordination may facilitate interaction with the environment and support development of higher order cognitive processes, including visuomotor integration (Campos et al., 2000). Once fine motor coordination is mastered and requires less attention, it is no longer strongly correlated with these other cognitive processes (Ackerman, 1988). Thus, these results are consistent with the automaticity account of the link between fine motor coordination to mathematics skills. However, they may also be consistent with the notion of a potential constrained effect (Paris, 2005); in other words, developing fine motor coordination beyond a certain threshold may not meaningfully contribute to more complex tasks or skills, such as mathematical learning.

Limitations

Several limitations are worth noting. First, despite inclusion of covariates to control for potential confounding factors (Selig & Little, 2012), results do not warrant causal claims and are better considered as a "stepping stone" in building an argument for a causal effect of these specific processes on mathematics skills and learning. Second, due to the data collection schedule, we could not investigate the longitudinal relations between variables from kindergarten through second grade in a single, parsimonious model. This resulted in some idiosyncratic differences between the two cohorts over time intervals, which seem to correspond (i.e., Time 2 to Time 3 for the kindergarten cohort and Time 1 and Time 2 for the first-grade cohort). For example, we observe a strong relation between Time 2 fine motor coordination and Time 3 mathematics skills for the kindergarten cohort but no such relation from Time 1 fine motor coordination to Time 2 mathematics skills. This and other differences could be due to the fact that the measurement of skills occurred at different times in development, the fact that there were different time lags between these two time points between cohorts, or even the fact that more constructs were being controlled for at Time 3 in kindergarten (i.e., all Time 1 *and* Time 2 constructs) than at Time 2 in first grade. In other words, such differences are idiosyncrasies possibly arising from the larger study design that should be addressed by future studies.

Third and relatedly, the more numerous occurrences of cross-lagged effects and stronger associations between processes in kindergarten, compared

to the later grades, could simply reflect differences in time intervals between time points rather than differentiation of skills, as we have suggested. In both cohorts, the time interval between Time 1 and Time 2 was about half the duration of that between Time 2 and Time 3, which could contribute to differences in the cross-lagged contributions of these constructs over time (Gollob & Reichardt, 1987). Nevertheless, our findings have strong theoretical support (e.g., Johnson, 2001), and we observed no cross-lag contributions in the first-grade cohort between Time 1 and Time 2. Given that, the reduction in the number of cross-lagged contributions as children progress in early elementary school is likely due to more than just assessment timing.

Fourth, the stability of constructs across time points, as well as the interrelations among constructs, raises the issue of multicollinearity and a suppressor effect (Burkholder & Harlow, 2003), which may explain, for example, the absent autoregressive effect from Time 2 and Time 3 in fine motor coordination in the kindergarten cohort, as well as the negative association between attention and mathematics skills from Time 1 to Time 2 in the first-grade cohort (Schroeder, Sjoquist, & Stephan, 1986). Fifth and finally, although well-established measures were used to assess children's motor and cognitive processes, only a single subtest was used as a measure of each of the constructs, and reliability varied for the measures in our sample. Reliability—in terms of test–retest correlation—was particularly low for the fine motor coordination and attention measures. This may indicate dynamic changes in these skills over the test periods, where children change dramatically disrupting relative individual differences among children. Low reliability would, however, attenuate rather than enhance the likelihood of finding significant associations, as well as the strength of associations. Still, it may be that variance in children's motor and cognitive abilities is related to other skills known to contribute to mathematics skills but not measured here. Thus, future studies should include several measures of each skill to more fully capture the constructs, as well as of other cognitive processes that have been linked to mathematics skills, such as visuospatial working memory (e.g., Li & Geary, 2013) and EF (e.g., Blair et al., 2008).

Implications and Future Directions

The fact that cross-domain prediction of constructs was obtained, over and above the strong within-construct stabilities, lends support to the notion that these processes do not develop in isolation but are, in fact, interrelated and interdependent (Diamond, 2007). The development and integration of these skills is necessary to successfully complete classroom-related tasks and make academic gains (Cameron et al., 2015). Understanding complex interrelations among hierarchically related skills may help practitioners inform and sequence instructional priorities, especially for children struggling with complex skills like mathematics, which appear reliant upon skills like visuomotor integration, which may in turn depend on fine motor coordination. Given that universal preschool programs appear just beyond the horizon in the United States, this research, and similar future studies with a young age group, could inform forthcoming policies governing curricular priorities and, more specifically, whether fine motor development is a worthwhile investment in early childhood.

The contribution of mathematics skills to visuomotor integration over time raises a challenging question: Could academic or mathematical development transfer to general development in visuomotor function? Certainly, many educational theorists would find this idea attractive, given that supporting child development in general has been considered by many to be part of education's purview (e.g., Montessori, 1976). Previous research suggests that improving children's mathematics skills through a promising age-appropriate mathematics intervention better prepares children for all school tasks (Sarama & Clements, 2004). However, to our knowledge, contributions of academic development to motor and cognitive development are largely unexplored and, yet, may have implications for the development of cognitive abilities throughout the life span. Taken together, the results of our study emphasize the complexity of the construct of mathematics skills and the need for continued efforts to understand its developmental underpinnings.

Conclusion

This study offers novel empirical evidence on the reciprocal associations between visuomotor integration, attention, fine motor coordination, and mathematics skills in the first years of formal schooling. Examining these associations over three time points in early childhood allowed us to describe the independent components that combine and coordinate to form the skills that are, in part, necessary for school success (Cameron et al., 2012). In doing so, we recognize that not all motor or cognitive skills should be regarded as the same, conceptually,

methodologically, or developmentally; yet, there is a codependency among skills that warrants consideration (Paris, 2005). In an age of accountability when direct instruction is often replacing more tactile- or sensorial-based learning activities in early grades (Bassok, Latham, & Rorem, 2016), understanding the role of motor and cognitive skills in supporting academic development is critical. Findings should motivate scholars, and any professionals working with children, to examine in greater depth the array of motor and cognitive skills that contribute to academic skills, including in mathematics.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Table S1. Descriptive Statistics by Grade for Site 1

Table S2. Descriptives by Grade for Site 2

Table S3. Zero-Order Correlations for All Variables Included in the Analyses for Kindergarteners (n = 135; Bottom Half of Table) and First Graders (n = 119; Top Half)